THE LOS ALAMOS 600 MJ, 1500 MW INERTIAL ENERGY STORAGE AND PULSED POWER UNIT*

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A 1430 MVA synchronous generator from a cancelled nuclear power plant has been installed and commissioned at Los Alamos National Laboratory (LANL) to be used as the pulsed power generator for physics experiments. The generator is mounted on a spring foundation to prevent dynamic forces from being transmitted to the substructure and into the ground. A 6 MW load-commutated inverter drive accelerates the machine from standstill to the maximum operating speed of 1800 rpm and from 1260 rpm to 1800 rpm between load pulses. The generator cooling method has been changed from hydrogen to air cooling to facilitate operation. A current limiting fuse, with a fuse clearing current of 90 kA, will protect the generator output against short circuit currents. An overview of the installation is presented. The paper also addresses the overload capability of the generator for pulsed loads.

1. Introduction

In the summer of 1987 LANL acquired all components of a 1430 MVA steam turbine generator from the Tennessee Valley Authority (TVA). The components had been shipped in 1981 and 1982 to the Hartsville, near Nashville, TN, plant site. The components were then stored in temporary buildings. The generator was designed to operate in a nuclear power plant as a steady state machine with 1430 MVA output power at 0.9 power factor. LANL intends to use the machine as a pulsed power source for physics experiments. Initially the generator will provide power and energy to a 60 T magnet, being designed at Los Alamos as part of the National High Magnetic Field Laboratory effort. The flat-top time of the magnet will be 100 ms. The magnet requires a power of 120 to 150 MW and an energy of nearly 300 MJ.

2. Generator Description

The total generator shaft train consists of a permanent magnet generator, a 315 mm slip ring bearing, the slip ring housing, the 630 mm non-drive end bearing, the generator, the 900 mm drive end bearing, the intermediate shaft, the 800 mm bearing, the thrust bearing, the turning gear with 400 mm bearing and the lube oil pump (Fig. 1). The installation is designed to extract the inertial energy of the rotor during a speed variation from rated speed to 0.7 rated speed. During such a speed change half of the energy at rated speed is extracted. The machine is accelerated in the morning from turning gear speed to 1800 rpm using the solid-state drive system. Before the load pulse occurs, the drive system is disconnected and the spinning machine is energized to its desired voltage, not to exceed 24 kV. During a maximum load pulse, the machine slows down to 1260 rpm in a few seconds. In the next ten minutes, the drive system again accelerates the rotor to 1800 rpm for the next load pulse. The reduction in speed from 1800 rpm to 1260 rpm releases 600 MJ of inertial energy. This energy is converted through power supplies and deposited in coils of the experiment. If a lesser amount of energy is required in an experiment, the rotor is accelerated to a speed less than 1800 rpm, to decrease the power costs. A small forbidden speed range around 1500 rpm is excluded as a speed for starting a pulse, because of the second critical at 1500 rpm. The total shaft train is 109 ft long and is mounted on a 112 ft × 40 ft inertia block. The main generator parameters are given in Table I.

The friction losses, consisting of bearing and windage losses, are 4.2 MW at 1800 rpm. The total lube oil inventory is 26,000 gallons. Figure 2 shows a view of the generator installation from the drive-end side. The shaft driven lube oil pump, the turning gear box and the intermediate shaft can be seen in the lower half of the picture with the generator in the upper half. The shaft train and the foundation are already designed to accommodate a flywheel, when energy needs are increased in the future. A flywheel with an energy of 2800 MJ can be installed in the given space. The space for the flywheel is currently bridged by the intermediate shaft.

3. Generator Building and Equipment Layout

The generator building is 200 ft long and 60 ft wide and has two floors, the operating floor and the basement floor. Except for the generator shaft train, all other components, including the lube oil tanks, batteries, drive and excitation system converters, are in the basement. Electrical equipment is located near the generator terminals. Personnel safety and ease of machine maintenance were the primary considerations in determining the equipment layout. A 32 ft × 12 ft control room is installed in the northeast corner on the operating floor. Figure 3 shows a cross section of the building. A 25 t overhead crane has been installed in the building. The crane capacity was chosen so that a routine maintenance of the generator could be performed. The heaviest piece to be lifted by the crane for removing the rotor is the 23 t bottom half of the 630 mm bearing pedestal. The building is long enough to house the rotor when it is removed from the stator.

A small switchyard is located on the east side of the generator building. It includes the station service, the drive and excitation transformers and 13.4 kV switchgear. The incoming power to the switchyard is provided by three 1000 mcm, 13.4 kV cables.

The generator has been installed at Los Alamos on a mesa, which also houses several nearby laser experiments. A concern that the pulsed generator load would result in soil vibrations and ultimately would have a negative effect on laser alignment was expressed. To minimize the problem, the generator uses a spring mounted foundation. Sixty springs, thirty on each side, resting on the 4 ft thick base concrete block, are installed under the inertia block. Four Belleville-type spring washers in a spring box provide the spring action. The inertia block (4800 t) and the generator (1200 t) have been raised 1.5 in. by hydraulic jacks in combination with the spring support adjustments and the springs have been adjusted to assure leveling of the inertia block.

4. Feasibility Study and Pre-Operational Testing

Before a contract was signed with TVA, LANL commissioned the generator manufacturer to evaluate whether the machine, with the given excitation system, could electrically and mechanically operate reliably under repetitive pulsed loading conditions. A load pulse with a peak power of 1400 MW was assumed. Several areas of concern were identified and investigated in considerable detail. These areas are mechanical stresses in the rotor shaft caused by fast torque changes, when the generator is connected to a large flywheel, and mechanical cyclic stresses in rotor components, such as the retaining rings, caused by a large number of starts from zero to rated speed. Without a flywheel, the generator will be stressed electrically and mechanically within operating limits by the cyclic pulsed loading. However, when the generator is connected to a 2800 MJ flywheel, a sudden change in electrical torque excites torsional oscillations in the shaft. The oscillations are hardly damped and the mechanical torque in the shaft between the generator and the flywheel can assume considerably higher than rated values. Ultimately the generator shaft will fail due to cyclic stress from these torque oscillations by mechanical fatigue. To avoid the excitation of the torque oscillation, the rate of change in real power must be limited to values in the order

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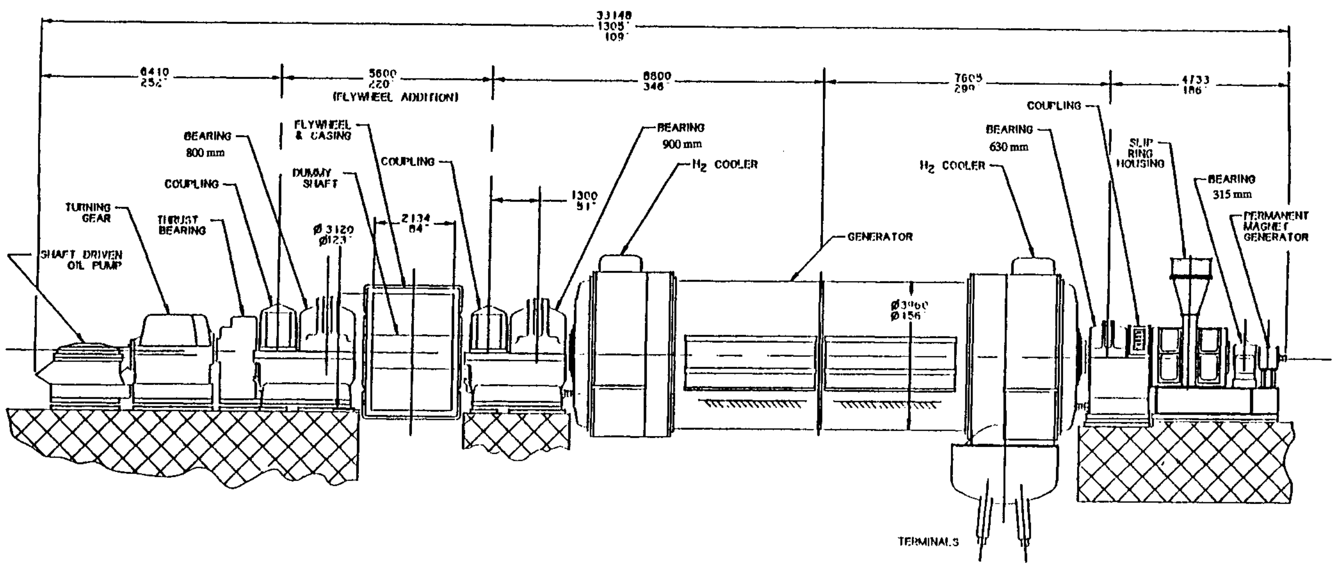

Fig. 1. Generator shaft train.

of 1 to 2 MW/ms. Cyclic stresses in critical components of the rotor, such as the retaining rings, the end windings, the main and slipring fans and the composited body, caused by a large number of run ups from zero to rated speed and load cycles between 1260 rpm and rated speed were also investigated. It was found that no excessive cyclic stresses for up to 1700 run ups from zero speed to rated speed and for 100,000 load cycles would occur. The manufacturer also recommended an inspection schedule, with the first inspection after 500 starts from standstill.

Table I. Generator Parameters.

Power rating	1430 MVA
Number of phases	3
Frequency	60 Hz
Number of poles	4
Voltage	24 kV + 5%
Current	34.4 kA
Synchronous speed	1800 rpm
Lower speed limit	1260 rpm
Energy of generator at 1800 rpm	1210 MJ
Extractable energy	600 MJ
Pulse repetition rate	10 min
Drive system rating	8000 hp
Stator weight	451 t
Rotor weight	234 t

Before shipment of the components to Los Alamos, the generator was tested electrically at Hartsville. The tests were similar to the electrical acceptance tests. These tests were repeated at Los Alamos after complete installation of the machine. The tests showed the stator and rotor in good electrical condition.

Besides the electrical tests, mechanical tests were performed on the retaining rings. The high-strength, nonmagnetic retaining rings were removed from the rotor in August 1989, before the rotor was installed into the stator, and subsequently inspected. The inspection consisted of a visual and fluorescent dye penetrant examination of all surfaces. Both rings tested well and showed very little corrosion pitting. If the rings had failed the test, purchase of new rings made of non-stress corrosion susceptible 18Mn18Cr steel would have been necessary.

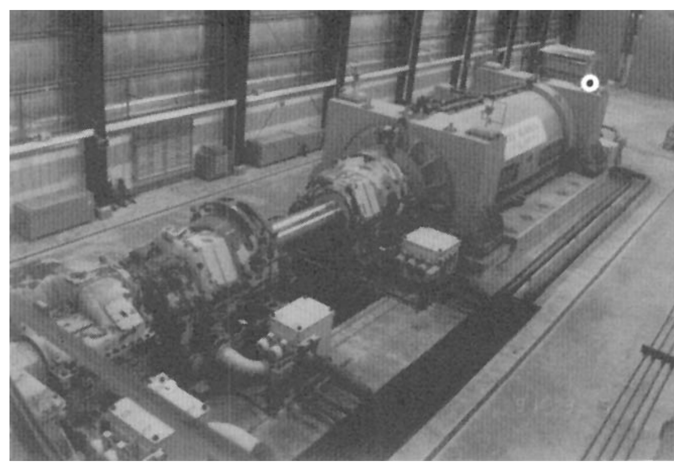

Fig. 2. View of the Los Alamos generator installation.

5. Hydrogen to Air Modification

The machine was originally designed to operate under 75 psi hydrogen pressure. Because of the low thermal loading of the machine during pulsed loads, simplicity in operation with air cooling and avoiding a tedious licensing procedure, LANL asked the generator manufacturer to investigate the possibility of running the machine in air. The manufacturer's investigation into this question revealed that the machine could be operated with air cooling, provided the machine was energized to 24 kV only during the pulse and certain modifications were made. Heaters and an air dryer have been installed in the machine, which heat and dry the air when the temperature is below 77° F, and the machine runs below 50 rpm. Shaft seals, using pressurized air out of the diffusers of the main fans, have been installed on both sides of the stator casing in order to provide controlled air flow through the specially installed air filters. The air modification has increased the windage losses by 300 kW at 1800 rpm compared to the 75 psi hydrogen operation. Using more optimized fans with a smaller diameter for air cooling, the friction losses could be reduced by 700 kW. At this time LANL is not considering replacing the fans because the intermittent mode of operation does not justify the additional expense.

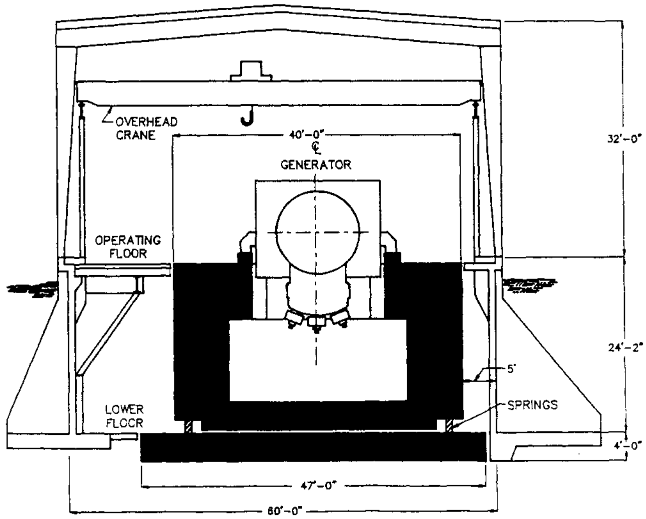

Fig. 3. Cross section of the generator building.

From a thermal standpoint, the conversion to air cooling has been successful. After a day of running, including four hours of operation at 1800 rpm, the generator air temperatures before the coolers were 139° F and the highest stator slot temperature was 150° F.

6. Excitation System

The static excitation system consists of the original three-phase, 10 MVA, 24 kV/0.792 kV, wye-delta, oil filled transformer, feeding four parallel connected six-pulse thyristor bridges. Each bridge has a no load voltage of 1050 V and a rated current of 3800 A. The thyristors are water cooled. Originally, the excitation transformer was designed to be connected to the 24 kV generator terminals. For pulsed operation it is desirable to take the excitation power from the utility system and, therefore, the excitation transformer was connected to the 13.4 kV utility system. The circuit of the transformer secondary winding was changed to a wye connection, resulting in approximately the same exciter no load voltage as designed originally. The exciter provides a field current of about 430 A during the drive mode operation of the machine and 2800 A for 24 kV no load voltage. During the pulse the field current can be raised up to 5100 A by the voltage regulator without exceeding the transformer rating. Because of the low exciter losses during pulsed mode operation compared to the 8600 A for steady state operation, the cooling water is being circulated only through the rectifiers without the use of the external heat exchanger.

The generator has been operated in the generator mode during commissioning to voltages up to 20 kV. Figure 4 shows a typical 20 kV voltage pulse, lasting approximately ten seconds. The field voltage, the field current and the generator voltage are shown. The voltage shows an overshoot to 21.86 kV, settling at its steady-state value of 20.38 kV. The field voltage rises to a peak of 900 V and the field current to 4480 A.

7. Drive System

An 8000 hp, solid-state, load-commutated inverter (LCI) drive accelerates the machine as a motor. The drive system consists of a 7.1 MVA, oil filled, six-phase converter transformer, a twelve-pulse rectifier, a 4 mH dc link reactor and a six-pulse inverter. The rectifier and inverter are water cooled. The maximum output voltage of the inverter is 4 kV. Because the low generator impedance could cause excessive fault currents in the inverter, a three phase 0.4 mH current limiting reactor has been installed between the generator terminals and the inverter. The LCI drive was sized to accelerate the rotor from 1260 rpm to 1800 rpm in 9 minutes. To accelerate the machine from 9 rpm turning gear speed to 1800 rpm will take about 25 minutes. The drive can be operated down to speeds of 30 rpm in the regenerative breaking mode.

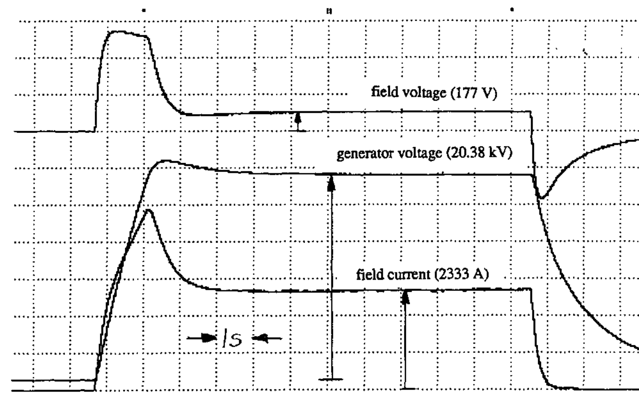

Fig. 4. Generator voltage for a 20 kV pulse.

In tests the generator was accelerated in 15 minutes from turning gear speed to rated speed. Figure 5 shows the generator stator phase voltage, current and speed as a function of time during a run-up from turning gear speed. The time to accelerate the rotor from 1260 rpm to 1800 rpm between load pulses is five minutes. The drive system can be used as a regenerative break. It takes the machine 40 minutes to coast down from 1800 rpm to standstill, while with regenerative breaking, the time is reduced to 7 minutes, as shown in Fig. 6. During the regenerative breaking the drive system returns to the utility system 871 MJ of energy of the 1260 MJ of energy stored in the rotor and intermediate shaft. The overload capability of the drive system was tested by running the generator for a short time at 1900 rpm. A preliminary flywheel design calls for a flywheel running in a vacuum. The friction losses from the flywheel are estimated to be 50 kW, however, the bearing losses will hardly change. The existing drive system will be adequate to accelerate generator rotor and flywheel with an extended run-up time. Figure 7 shows different parameters during a heat run test at 1800 rpm, which lasted for four hours and included an overspeed test to 1900 rpm to test the drive system capability. The heat run test was followed by five acceleration/deceleration cycles between 1200 and 1800 rpm to simulate load pulses. This load test was thermally more demanding than the expected loading during cyclic operation. The figure shows the speed, the metal temperature of the most heavily loaded bearing (630 mm bearing) and the cooling air temperature before the coolers. No alarm levels were reached.

8. Generator Performance Limits

Because of the lower dielectric strength of air compared to 75 psi hydrogen and the reduced air density at Los Alamos, located at 7300 ft elevation, it cannot be expected to run the machine at a voltage higher than 24 kV. With respect to the current, the thermal limit of the machine is not being reached during pulsed operation. A machine similar to the Los Alamos machine has been successfully short circuit tested at 60% of rated voltage. Peak currents up to 200 kA were measured. Using the current overload capability the Los Alamos machine might provide 20 to 50% overload for a limited amount of repetitive pulses, resulting in a pulsed power rating in the order of 2000 MW. It is understood that during overload tests critical components, such as rotor retaining rings and stator end windings, must be carefully instrumented and observed on a shot by shot basis to avoid damage. A five percent overspeed will raise the extractable energy to 720 MJ. The addition of a flywheel will raise the energy to 2000 MJ extractable. By overspeeding the machine additional 400 MJ could be extracted. The inductances of the generator and the excitation system limit the rate of energy extraction. A reasonable energy extraction rate is in the order of 1 to 2 MJ/ms.

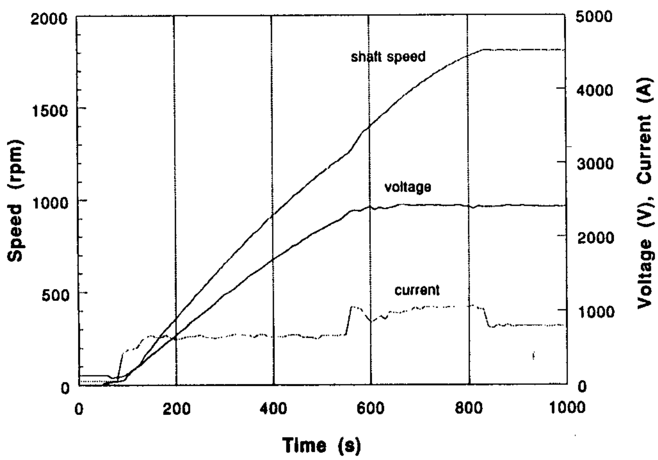

Fig. 5. Generator parameters during run-up.

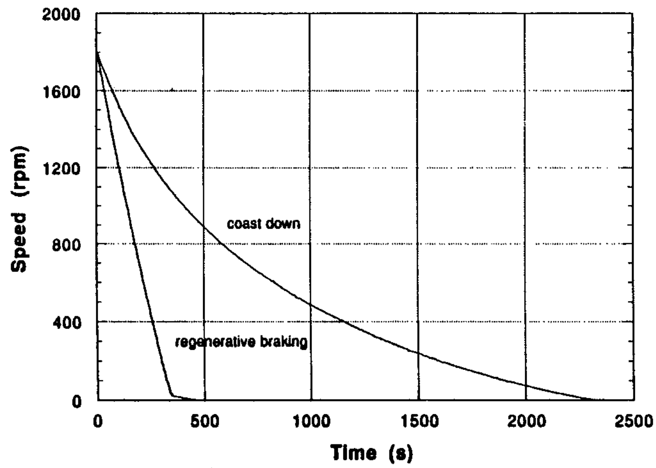

Fig. 6. Generator run-down curves.

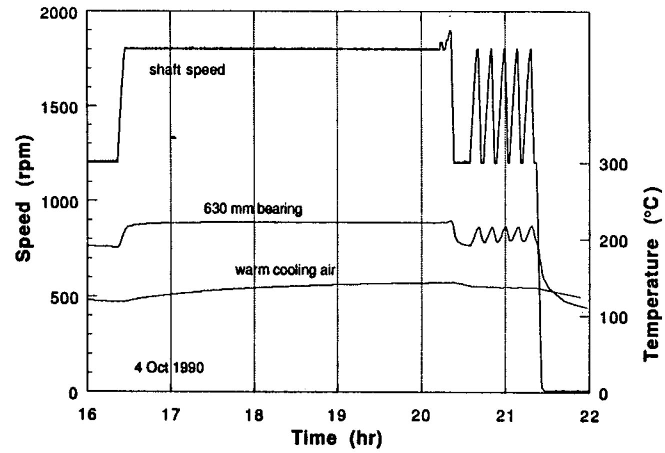

Fig. 7. Generator parameters during a heat run and speed cycling test.

9. Summary

A 1430 MVA generator from a cancelled nuclear power plant has been installed at Los Alamos to provide power and energy to experiments, which require hundreds of megawatts repetitively for several seconds per load pulse. The necessary design modifications of the machine have been made, in particular, the hydrogen-to-air cooling change. The generator has been tested both in the drive mode and in the generator mode under no load condition. The drive system has accelerated the rotor to 1900 rpm, a 5% overspeed and has simulated the ten minute load cycle between 1260 and 1800 rpm by accelerating and regeneratively breaking the machine. No excessive temperatures have been measured in the machine.

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